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Atmospheric connections with the North Atlantic enhanced the deglacial warming in northeast China

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ABSTRACT

Variations in atmospheric circulation across the last deglaciation in the northernmost monsoon-influenced regions of Asia are not well constrained, highlighting a fundamental gap in our understanding of Asian climate. Here we reconstruct continental air temperatures for northeast China across the last deglaciation (past 16 k.y.), based on the distribution of bacterial branched glycerol dialkyl glycerol tetraethers in a sequence of the Hani peat (Jilin Province, northeast China). Our results indicate large (as much as 10 °C) oscillations in temperature in northeast China across the deglaciation, oscillations significantly larger than observed in other temperature records from low-latitude or same-latitude East Asia, but consistent with climate model simulations. This enhanced magnitude, as well as the timing of temperature variations, provides evidence for atmospheric teleconnections with high latitudes; in particular, we suggest that high-latitude cooling associated with Arctic ice expansion and changes in Atlantic Meridional Overturning Circulation enhanced the intensity and lowered the temperature of Eurasian mid-latitude westerlies and northwesterly winds over East Asia during the last glacial, delivering cold air masses to northeast China. During the deglaciation the westerlies and therefore delivery of cold air masses weakened, amplifying the deglacial warming in this region. We conclude that changes in North Atlantic climate had a particularly strong impact on the northernmost parts of the East Asian monsoon-influenced area.

INTRODUCTION

Variations of the East Asian monsoon (EAM) systems over the last deglaciation are largely based on terrestrial records (An et al., 2012; Wang et al., 2001). The nature and locations of most of these records mean that they are largely restricted to summer monsoon precipitation reconstructions, and temperature records are scarce (Peterse et al., 2014), especially for continental monsoon areas. The northernmost monsoon-influenced regions are likely to be particularly sensitive recorders of wider climate variations, given the interactions of the EAM and the westerlies (Nagashima et al., 2011). However, climate records are limited to a small number of paleoecological and paleohydrological records from peat deposits and maar lake sediments (Zhou et al., 2010; Schettler et al., 2006). Thus, variations in atmospheric circulation across the deglaciation in this region are not as well understood as other parts of the EAM area.

Peat deposits are widespread in northeast China, offering the potential to reconstruct climate. Previous studies from peat sequences in northeast China documented wet conditions during the deglacial (Zhou et al., 2010).

Although peat cellulose $\delta^{18}\text{O}$ records from the Hani peat have been used to qualitatively reconstruct temperature changes since the deglaciation (Hong et al., 2009), quantitative temperature records from this region are lacking. Such records are critical for interrogating models of Asian climate change. For example, proxy evidence has suggested that the westerlies were stronger during the last glacial (Nagashima et al., 2011); if so, that would have amplified these cold periods in northeast China relative to temperature changes observed in other EAM regions, including the Loess Plateau and Lake Suigetsu in Japan (Nakagawa et al., 2005; Peterse et al., 2014). Therefore, development of robust temperature records from northeast China and a comparison with those from other areas, and particularly more southern Asian sites not as strongly influenced by the westerlies, would allow changes in atmospheric circulation patterns and the extent of monsoon influence to be deciphered.

Here we apply to the northeast China Hani peat sequence a recently developed peat-specific proxy for mean annual air temperature ($\text{MAAT}_{\text{peat}}$) (Naafs et al., 2017) based on the distribution of bacterial branched glycerol dialkyl glycerol tetraethers (brGDGTs) (Sinninghe Damsté et al., 2000). This provides an exceptional opportunity to develop new temperature records and test the aforementioned hypotheses. The Hani peat sequence (42°13'N, 126°31'E; Fig. 1) spans the past 16 k.y., allowing us to directly evaluate the magnitude of regional terrestrial air temperature changes across the deglaciation. The sampling resolution of ~100–200 yr allows us to also examine millennial-scale events.

METHODS

An 885 cm peat sequence was obtained using a peat corer. The core was ^{14}C dated by accelerator mass spectroscopy (AMS; 10 samples between 48 and 880 cm depth), with ages obtained using Bayesian age-depth modeling software Bacon (Blaauw and Christen, 2011). The model demonstrated that the core spans the past 16,000 calibrated years (Table DR1 and Fig. DR1 in the GSA Data Repository¹). Freeze-dried, homogenized samples were extracted using the method of Zheng et al. (2014). The total lipid extracts were base hydrolyzed in 1M KOH/MeOH (5% H_2O in volume) at 80 °C for 2 h; the solution was then extracted with *n*-hexane. The extract was separated into apolar and polar fractions using silica gel flash column chromatography with *n*-hexane and MeOH as eluents, respectively. Half of the polar fraction was filtered through 0.45 μm polytetrafluoroethylene

¹GSA Data Repository item 2017353, Table DR1 and Figure DR1 (results of AMS ^{14}C dating), and Figure DR2 (temperature series based on the data and simulation), is available online at <http://www.geosociety.org/datarepository/2017/> or on request from editing@geosociety.org.

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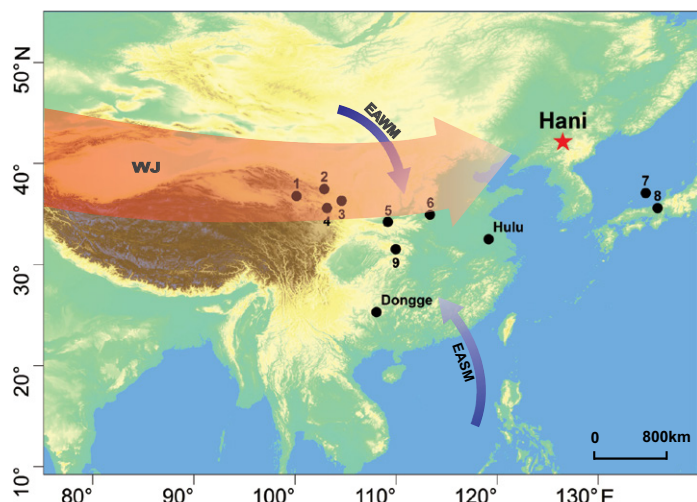


Figure 1. Location of the Hani peat in northeast China and other sites in the East Asian monsoon (EAM) region: 1—Lake Qinghai, 2—Gulang loess, 3—Jingyuan loess, 4—Yuanbao loess, 5—Lantian loess, 6—Mangshan loess, 7—marine sediment core MD01-2407, 8—Lake Suigetsu, 9—Dajihu peat. EASM—East Asian summer monsoon, EAWM—East Asian winter monsoon, WJ—Westerly jet.

syringe filters and dried. The brGDGT analysis followed the procedure of Yang et al. (2015; see the Data Repository).

Based on the global peat calibration of Naafs et al. (2017), Hani peat temperatures range from -5.5 to 12.5 °C, with a mean value of 7 °C. The instrumental MAAT over the past 60 yr ranges from 3.8 to 7.4 °C in the region (data from <http://data.cma.cn/>), in agreement with the MAAT_{peat} reconstructions for 3 surface peats from the Hani peatland: 5.5 °C, 3.5 °C, and 3.7 °C. Despite that similarity, it is important to note that this is one of the first applications of this proxy to reconstruct past MAAT.

RESULTS

The Hani MAAT_{peat} record reveals that air temperatures in the area varied markedly over the past 16 k.y. (Fig. 2A). We note that variations in the MAAT_{peat} record do not coincide with the peat cellulose $\delta^{18}\text{O}$ temperature record from the same setting (Fig. 2B); this might be due to the mixed signal of precipitation and temperature recorded by the latter (Hong et al., 2009, and references therein).

Temperatures obtained using our approach varied between -5.5 and 3 °C (± 4.7 °C) during the Oldest Dryas (OD, ca. 16.2–14.5 ka), i.e., 2 – 10 °C cooler than the modern values. The lowest temperature occurred at 15.8 ka during the peak of the OD. Higher temperatures (~ 1 – 3 °C) from ca. 15.2 to 14.5 ka appear to correspond to pre-Bølling-Allerød (B/A) warming or late Heinrich 1 warming, as recorded in the mid-latitude North Atlantic (Naafs et al., 2013). During the B/A, from 14.5 to 12.6 ka temperatures were higher, varying between 4 °C and 8 °C. Temperatures then decreased by 2 – 3 °C during the Younger Dryas (YD) to values of ~ 5 °C. From 11.5 to 10.7 ka, corresponding to the Preboreal event, MAAT_{peat} indicates even higher values, from 7.0 to 12 °C. MAAT_{peat} continued to vary during the Holocene. From 10.7 to 6.0 ka, temperatures rose stepwise, with 2 cool events at 10.6–10.2 and 8.6 ka, before reaching maximum values of ~ 11 °C during the early Holocene from 8.0 to 6.0 ka. Following the early Holocene, temperatures at Hani gradually decreased to values of ~ 5 °C, close to the observed temperature at Hani across the past 60 yr (4 – 7.5 °C).

DISCUSSION AND CONCLUSIONS

MAAT_{peat} variations at Hani are large and it is possible that MAAT_{peat} has heretofore unknown complications resulting in overestimates of temperature variation. The root mean square error for the entire calibration

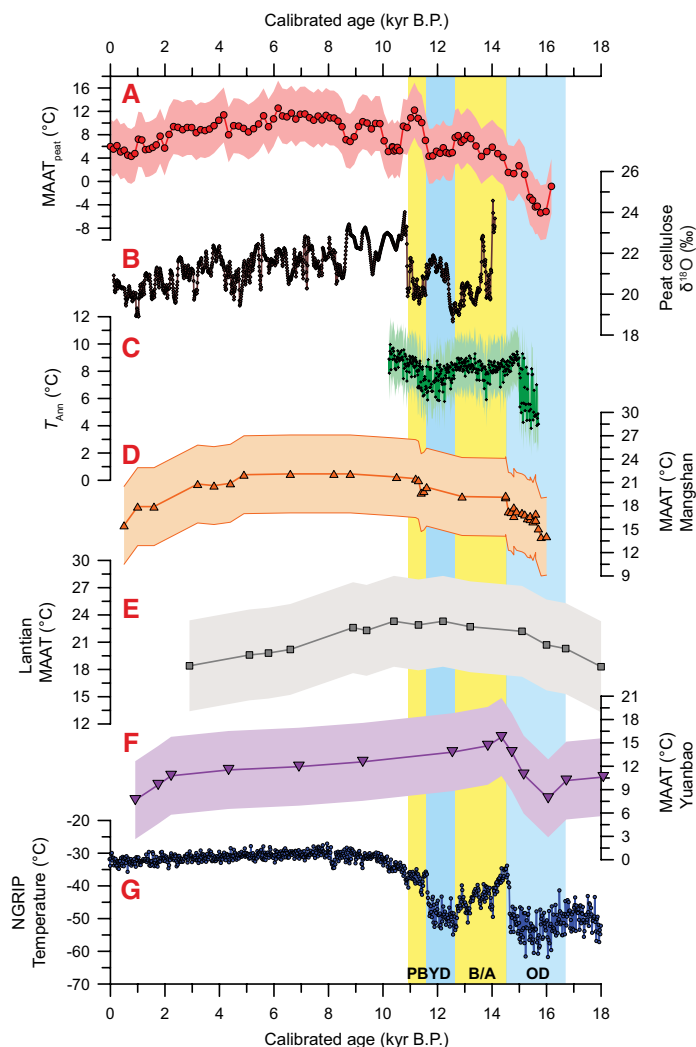


Figure 2. Temperature variations over the last deglaciation in the Hani peat region (Jilin Province, northeast China) and other areas. **A:** Peat-specific proxy for mean annual air temperature (MAAT_{peat}) based temperatures in Hani region. **B:** $\delta^{18}\text{O}$ temperature proxy from Hani peat cellulose (Hong et al., 2009). **C:** Mean annual temperatures (T_{ann}) derived from pollen records in Lake Suigetsu (Nakagawa et al., 2005). **D:** MAAT derived from branched glycerol dialkyl glycerol tetraethers in Mangshan loess (Peterse et al., 2014). **E:** MAAT derived from Lantian loess (Gao et al., 2012). **F:** MAAT derived from Yuanbao loess (Jia et al., 2013). **G:** $\delta^{18}\text{O}$ -based North Greenland Ice Core Project (NGRIP) temperatures (Cuffey and Clow, 1997; Andersen et al., 2006). PB—Preboreal, YD—Younger Dryas, B/A—Bølling-Allerød, OD—Oldest Dryas.

data set is relatively large, 4.7 °C (similar to that of other GDGT-based temperature proxies), but at least some of the variables that likely exert secondary controls, such as vegetation type, appear not to have changed significantly in the Hani sequence. Consequently, we consider the MAAT record to be robust, but acknowledge the issues associated with the application of new proxies.

Our temperature record from the Hani core is the only one available from northeast China. The closest available temperature record across the deglaciation is from the pollen data set at Lake Suigetsu, more than 1000 km away and located on the coast of the Sea of Japan in a different climatic zone (Fig. 1). The magnitude of deglacial temperature change at Hani ($>10 \pm 4.7$ °C) is much larger than the pollen-based mean annual temperature change of 3 – 5 ± 2 °C between stadial and interstadial phases recorded at Lake Suigetsu (Nakagawa et al., 2005) (Fig. 2C). It is also larger than the 5 – 7 ± 5 °C warming recorded in the distal (>2000 km from

the Hani peat) Loess Plateau Mangshan sequence (Peterse et al., 2014), Lantian loess (Gao et al., 2012), and Yuanbao loess (Jia et al., 2013), based on brGDGTs (Figs. 1 and 2D–2F), although these are lower resolution records and based on outdated analytical methods and calibrations that might underestimate the extent of temperature change (De Jonge et al., 2014). The Hani temperature variation is also larger than the temperature change suggested by the pollen record from the Dajihuo peat, located much farther to the south (Zhu et al., 2008; Fig. 1). These results indicate that the Hani peat region provides a unique deglacial temperature record compared to that recorded at other sites in Asia.

A relatively small deglacial temperature change is suggested by the Northern Hemisphere temperature stacks, which generally yield last glacial temperatures 3–4 °C lower than those of the Holocene (Shakun et al., 2012). However, sea-surface temperature reconstructions from different ocean basins suggest that the magnitude of warming is lower at low latitudes (1–3 °C) in comparison to higher latitudes (3–6 °C; Clark et al., 2012). Large temperature differences between the last deglaciation and the Holocene were restricted to the high-latitude ocean (~7–12 °C) and over Greenland (~13–19 °C) (Fig. 2G; Waelbroeck et al., 2001; Cuffey and Clow, 1997; Andersen et al., 2006). Therefore, compared with the low-mid latitude oceans and other EAM regions, the reconstructed temperature change at Hani is large, but it is similar to changes recorded at high northern latitudes.

The abrupt transitions at the beginning and end of the YD observed at Hani are similar to those recorded in the ice core records (Figs. 2A, 2G). Although the B/A is associated with an inferred intensification of the summer monsoon in cave records (Wang et al., 2001), these records do not exhibit the same rapid transitions. Moreover, a remarkable Preboreal event observed in North Greenland Ice Core Project (NGRIP) cores (ca. 11.5–10 ka) (Fig. 2G) is also apparent in the Hani record (ca. 11.5–10.7 ka), but absent in Chinese speleothem records. The millennial temperature oscillations observed in North Atlantic deglacial records are also apparent in the Hani temperature record but missing in the lower resolution records from Mangshan and Lantian on the southern Loess Plateau, Yuanbao on the western edge of the Loess Plateau (Fig. 2), and Jingyuan on the north-western Chinese Loess Plateau (Fig. 1; Sun et al., 2012). The absence of these millennial temperature variations in the loess records could arise either from signal smoothing or dilution due to how the geochemical signatures are generated in the loess (Peterse et al., 2014), or to the lower resolution and discontinuity of loess sequences (Porter and An, 1995).

The Hani record appears to document enhanced temperature change, compared to other Asian regions, over the past 16 k.y. This is generally consistent with temperature changes simulated using the National Center for Atmospheric Research Community Climate System Model version 3 (CCSM3) (Liu et al., 2009) that reveal a dramatic increase of 5–8 °C from the OD to the Preboreal (Fig. 3; Fig. DR2), similar to the temperature change of 6–10 °C suggested by the proxy data. The simulated spatial pattern of temperature change (Fig. 3) indicates that the OD to Preboreal MAAT change in northeast China was larger than in other regions, consistent with the proxy data.

Because vegetation appears to have been stable in the Hani sequence, we conclude that vegetation cover and surface albedo had a negligible role in amplifying temperature change. Instead, we mainly ascribe the large and abrupt temperature changes recorded in the Hani peat across the deglaciation to changes in the delivery of cold air from the high-latitude North Atlantic to northeast China. Other sites from Asia also record these changes, but the effect appears to be amplified at Hani, the only record from northeast China. Based on the fact that the Hani peat record also exhibits a particularly strong response to millennial events (i.e., B/A and YD), we ascribe the differences between it and other Asian sites to particularly strong North Atlantic connections.

Expanded sea ice extent over the North Atlantic (Zhu et al., 2014) and the slowing of Atlantic Meridional Overturning Circulation (AMOC)

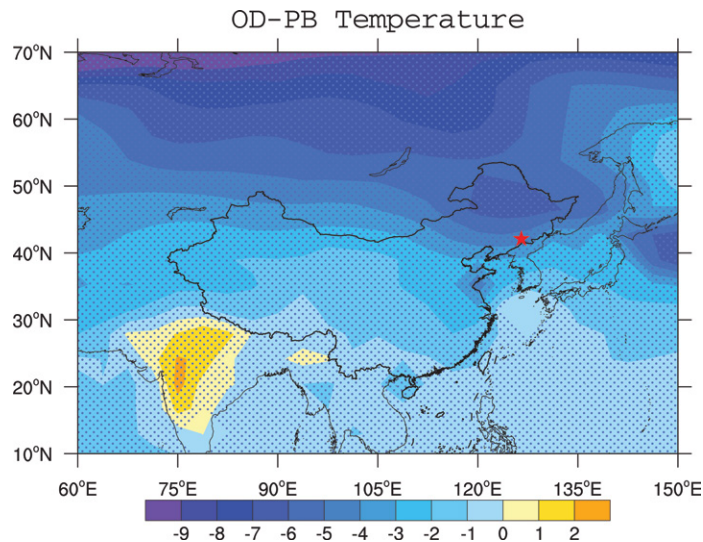


Figure 3. National Center for Atmospheric Research Community Climate System Model version 3 simulated distribution of annual mean surface air temperature difference (in °C) between Oldest Dryas (OD) and Preboreal (PB). Red solid star represents the location of the Hani peat (northeast China). The simulation data were extracted from Liu et al. (2009). The stippled areas show a confidence level higher than 95% using a Student's t-test.

during stadial intervals (McManus et al., 2004) likely cooled the high latitudes, lowering the temperature of downstream East Asia regions via cold air advection. At the same time, severe cooling in the high northern latitudes across the Eurasian continent increased the meridional thermal gradient between the low and high latitudes and could have intensified the mid-latitude westerlies and the East Asian winter monsoon. Stronger westerly winds in the upper troposphere and northwesterly winds in the lower troposphere that bring more cold air to Asia and northeast China in particular could have amplified the cooling at Hani during the last glacial compared to other Asian sites. There is supporting evidence from Lake Qinghai in the northeastern Tibetan Plateau (An et al., 2012), Central Asia (Vandenberghe et al., 2006), and the Chinese Loess Plateau (Porter and An, 1995; Vandenberghe et al., 2006; Sun et al., 2012) that indicate that the westerlies were stronger during the last glacial. Other records from arid Central Asia also indicate that the westerlies weakened during the early Holocene (Chen et al., 2016). The interplay of the westerlies with monsoon systems also could have been important: the last glacial could have been characterized by a stronger atmospheric pressure gradient between high and low latitudes, which might not only have enhanced the westerlies but weakened the East Asian summer monsoon and strengthened the East Asian winter monsoon. In addition, a reduction of southerly winds due to a weakening of the North Pacific High over the northwest Pacific (Meyer and Barr, 2017) might have played a role.

In conclusion, we argue that stronger mid-latitude westerly winds in combination with colder Atlantic cold air masses related to Arctic sea ice expansion and slowing of AMOC likely led to more cold air being transported eastward and caused extremely low temperatures during the OD in northeast China, observed in both proxies and CCSM3 simulations. Regardless of the primary control, the dramatic variations in the Hani peat temperature record provide new and strong evidence for teleconnections between northeast China and the North Atlantic on orbital time scales.

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